34 p.

OTS PRICE

XEROX $ 3.60 ph

MICROFILM $ 1.22 mf

FIFTH QUARTERLY REPORT

PERIOD 1 JULY 1963 – 30 SEPTEMBER 1963

N64 11297*

CODE-1

(NASA CR 52545) OTS

RESEARCH AND DEVELOPMENT OF AN OPEN-CYCLE FUEL CELL SYSTEM

(NASA Contract No. NAS8-2696)

Proposal Request Number TP 2-831321

Prepared for

George C. Marshall
Space Flight Center
Huntsville, Alabama

By

SPACE AND DEFENSE
SCIENCES DEPT.

RESEARCH DIVISION

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31 OCTOBER 1963

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FOREWARD

This report was prepared by the Space and Defense Sciences Department, Research Division, Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin, under NASA Contract NAS8-2696. The work was administered under the direction of the Electrical Components and Power Supplies Section, Astrionics Division, NASA, Huntsville, Alabama. Mr. Richard Boehme is the technical supervisor for NASA.

This Fifth Quarterly Report covers the work completed from 1 July 1963 to 30 September 1963 and is submitted as per the 8 February 1963 Contract Modification.

Management direction at Allis-Chalmers includes Mr. Will Mitchell, Jr., Director of Research, and Dr. Powell Joyner, Mr. D. T. Scag and Mr. W. W. Edens, Assistant Directors of Research. The project is supervised by J. L. Platner, Section Head, and P. D. Hess, Chief Engineer. The Project Leader is D. P. Ghere.

The report was written by J. Euclide, R. Opperthauser, C. Pax, D. Ghere, and B. Nichols.

Dr. R. Jasinski and Mr. J. Huff are consultants for the gas chromatography analysis.

ABSTRACT

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This report summarizes thermal design considerations for a fuel cell system including thermal efficiency, thermal optimization of fuel cell plates, and various cooling systems.

Operation of the Dynamic Vapor Pressure Control breadboard system, which was revised to include a liquid cell cooling system and to eliminate the oxygen recirculation system, is reported.

Included is a discussion of various methods of fabricating fuel cell plates.

AUTHOR

TABLE OF CONTENTS

LIST OF FIGURES

1.0 SUMMARY

During this quarter, thermal design of fuel cells and fuel cell systems have been studied. A simplified method of determining fuel cell plate dimensions for minimum weight consistent with satisfactory temperature gradient has been developed. Secondary cooling systems using either gas or liquid as cooling fluids are being investigated and feasibility tests have started. The Dynamic Vapor Pressure Control breadboard system was modified by the substitution of an oxygen purge system for the oxygen recirculation system and the incorporation of a liquid cooling system for the fuel cell. After tests of this revised system proved satisfactory, the system was again revised to include an improved condenser-separator and a different type of coolant mixing valve. This system is presently operating satisfactorily.

Of the various methods of fabricating fuel cell plates which have been investigated, die casting appears to be the most economical for large quantities of identical plates, provided a suitable alloy can be developed. Thus far conventionally machined plates appear to be the best quality. Various other methods appear promising in special cases.

2.0 INTRODUCTION

The major effort during the period of this report was in the area of thermal design of a space oriented fuel cell system. This included thermal design of the fuel cells themselves as well as design of a cooling system. Further testing of the revised breadboard system is also reported. Various methods of fabricating the fuel cell plates are being investigated and the results to date are discussed.

3.0 THERMAL DESIGN CONSIDERATIONS

Thermal design of a fuel cell system depends first of all on the thermal efficiency of the fuel cell, which determines the amount of heat which must be dissipated. Secondly, this heat must be conducted out of the cell through the electrode holder plates without causing a detrimental temperature differential across the surface of the cell. The cooling system must then pick up this heat from the cell and reject it from the fuel cell system.

3.1 Fuel Cell Thermal Efficiency

Characteristic of fuel cell operation, some waste heat is produced during the fuel cell reaction. The amount of waste heat produced depends on the thermal efficiency and the power output as shown in the following analysis.

The thermal efficiency, assuming 100% current efficiency, is defined as:

$$N_t = \frac{\Delta F}{m \Delta H^\circ} \times 100$$

ΔH° = Enthalpy of reaction per mole of product

ΔF = Observed free energy change (Observed electrical work)

m = Determined moles of reactant consumed

Explicit definition of ΔH° and ΔF° requires an explicit definition of reactions taking place in the fuel cell. Operating temperature must also be defined since the thermodynamic properties (ΔF° and ΔH°) are temperature dependent properties. Therefore, for the following discussions, the efficiencies are based on the following defined reactions:

$$H_2 \text{ (aq.)} + 1/2\, O_2 \text{ (aq.)} \xrightarrow{25^\circ C} H_2O \text{ (liq).}$$

Since:

$$\Delta F \approx -n \; \Delta m f E,$$

where	n	=	equivalents per mole of reactant
	f	=	Faradays constant
		=	96,500 coulombs per equivalent
	E	=	Observed voltage
	Δm	=	Moles of reactant consumed

ΔF observed is proportional to E and $\Delta F°$ is proportional to $E°$ (1.23 volts). Thus, with reactants and products at 25° C, the thermal efficiency may be determined from the relationship $N_t = E/1.23 \times \frac{\Delta F°}{\Delta H°}$ or $N_t = .67\,E$, where E/1.23 is the ratio of the actual cell voltage to the theoretical cell voltage. The last term, $\frac{\Delta F°}{\Delta H°}$, is the maximum possible thermal efficiency. The total heat produced is dependent on the load and efficiency as previously stated, and can be easily determined from the relationship:

$$U = P\left[\frac{1}{N_t} - 1\right]$$

or

$$U = P\left[\frac{1}{.67\,E} - 1\right]$$

where P = power in watts

U = heat in watts

In an operating fuel cell, water is formed as a result of the reaction and must be removed in order to maintain good performance. If this water is removed as a vapor, a considerable amount of heat will be removed with the vapor. The amount of heat energy exhausted in this manner is in direct relationship to the amount of water produced in the cell and to the cell temperature.

The relationship for determining the amount of water produced per hour in an operating cell is:

$$W = 0.337\ I\ N$$

where I = amperes
N = number of cells
W = grams of water per hour

When the total heat energy of vaporized water at 93.3° C is taken as 0.757 watt-hours/gram, then the heat rejected with the vapor is:

$$U' = 0.256 \times I\ N$$

where U' = watts

The heat rejected in this manner usually amounts to about one third of the total heat burden under normal operation.

If the water vapor is condensed and collected, the heat of condensation must be rejected from the fuel cell system by the fuel cell cooling system and the thermal advantage for the system as a whole is no longer gained. The reduced heat burden would still apply to the fuel cell assembly, however.

3.2 Thermal Optimization of Fuel Cell Plates

A fuel cell module with a given cell area can be built with numerous cell configurations. It is the object of this discussion to show how the minimum weight configuration may be determined subject to requirements of heat removal from the cell. This is done by expressing weight as a function of cell configuration variables and determining the minimum point.

Only the weights of the fuel cells and canister need be considered since weights of other components of the system are negligibly affected by cell configuration.

Rectangular cells externally cooled with fins on two edges are used due to ease of reactant manifolding and heat removal. The cell considered consists of two cell plates, whose weights depend upon cell configuration; electrodes; electrolyte and capillary membranes; all of whose weights are independent of cell configuration. A sketch of a cell plate is shown in Figure 1. The plate is considered as three separate regions (active cell region, seal region, and fins) to clarify calculations.

The weight of the active cell region of one cell plate $= \rho_1 A \delta_a F_W = W_1$

where:

ρ_1	=	density of plate material
A	=	active cell area
δ_a	=	thickness of one cell plate in active cell region
F_W	=	fraction of metal remaining in active cell region after manifolding grooves for gas distribution are machined

If the two plates in one cell have different thicknesses, the average between the two values is used. Other parameters which are not the same for the two plates are handled in the same manner throughout this analysis.

Weight of seal region of one cell plate is approximately $= 2\rho_1 \ell_S (\ell_1 + \ell_2)\delta_S = W_2$

where:

ℓ_S	=	width of seal region
ℓ_1	=	length of uncooled side of active cell region
ℓ_2	=	length of cooled side of active cell region
δ_S	=	thickness of plate in seal region

Weight of fins on one cell plate is approximately $= 2\rho_1 \ell_2 \ell_F \delta_F = W_3$

where:

ℓ_F	=	width of fin
δ_F	=	thickness of fin

The cell plates are usually plated with a thin metal layer for protection from corrosion due to chemicals present in the fuel cell.

Weight of plating for corrosion protection on one cell plate is approximately =

$$2\rho_P A_P \delta_P F_P + 4\rho_P \ell_S(\ell_1+\ell_2)\delta_P + 4\rho_P \ell_F \ell_2 \delta_P = W_4$$

the terms referring respectively to plating on active region, seal region, and fins,

with: ρ_P = density of plating material

δ_P = thickness of plating

F_P = surface area of active cell region with manifolding grooves compared to the surface area of a flat plate of equal size

Weights of electrodes, electrolyte, asbestos membranes, bolts, and end plates are essentially constant and are therefore omitted from this consideration of weight variation.

Canister weight is small compared to fuel cell reactor weight and can be approximated by: $\rho_C \delta_C \ell_C^2 (\ell_2 + \ell_1 + 2\ell_S) = W_5$

where: ρ_C = density of canister material

δ_C = thickness of canister wall

ℓ_C = length of canister

For a fuel cell reactor composed of N cells (2 N cell plates), the combined reactor and canister weight affected by configuration is given by:

$$W = 2N\left[W_1 + W_2 + W_3 + W_4\right] + W_5 \qquad (1)$$

This problem is simplified by noting that values of many of these parameters are constants for a specific fuel cell application and can be determined from the following considerations.

N and A	are determined from output power and voltage requirements and cell performance characteristics
F_W, F_P	are determined from required manifolding
ρ_1	property of cell plate material which is selected for low density and high thermal conductivity
ℓ_S	determined by minimum seal width requirements
δ_S	determined by minimum thickness allowable for sealing and manifolding into cell
ℓ_F	determined from minimum area consistent with good heat transfer to coolant flowing over fins
δ_F	determined from minimum thickness consistent with machining and handling requirements
ρ_P	determined from the plating material selected for corrosion protection
δ_P	determined from minimum plating thickness required for corrosion protection
ρ_C	determined from material selected for the canister
δ_C	minimum canister thickness consistent with handling and fabrication requirements
ℓ_C	canister length fixed by seal thicknesses and number of plates in reactor

Then, Equation (1) expresses weight as a function of three variable plate dimensions (ℓ_1, ℓ_2, and δ_a) with all other parameters constant for a specific application. In order to express weight as a function of a single configuration dimension, the following relations are used. From the constant area condition we obtain

$$\ell_1 \ell_2 = A \tag{2}$$

For minimum weight δ_a should be a minimum. This minimum value of plate thickness is determined by the thickness required for conduction of waste heat from the inside of the cell to the cooling fins.

Assuming constant temperature along cooling fins and no heat loss through end plates the problem becomes a one dimensional problem of heat conduction in a plate with constant heat flux into the plate surface. For a flat plate, the thickness, δ, and temperature drop, ΔT, in a length, x, are related by:

$$\delta = \frac{q_p x^2}{2K\Delta T}$$

where q_p = heat input per unit area per plate
K = thermal conductivity of the plate

In the fuel cell the thermal resistance between plates is quite low so that the temperatures of both plates are very nearly equal. Therefore the plates remove heat depending upon their thicknesses and practically independent of which side of the cell the heat is generated.

Average values of the plate thicknesses can therefore be used. For the cell plate substituting $q_p = \frac{q}{2}$, $\delta = \frac{\delta_a}{F_\ell}$ and $x = \frac{\ell_1}{2}$ then

$$\delta_a = \frac{q \ell_1^2 F_\ell}{16 K \Delta T_1} \tag{3}$$

where ΔT_1 = permissible temperature difference between edge and center of cell (determined from operating characteristics)

F_ℓ = ratio of thermal resistance of plate with manifold grooves to the thermal resistance of an equal thickness plate of the same material without grooves

K = thermal conductivity of plate material

q = cell cooling load per unit cell area per unit time

The value of q is given as the heat produced per unit area per cell by the $H_2 - O_2$ reaction minus the heat removed with the product water per unit area,

$$q = \frac{\sqcup - \sqcup'}{NA} \tag{4}$$

where $\sqcup = \dfrac{1}{.67\,E} - 1$ watts

$\sqcup' = (.256)\ I\ N$ watts with the fuel cell operating at 93.3° C (see page 5)

I = total current in amps at rated load

E = voltage per cell at rated load

N = number of cells comprising the fuel cell reactor

Choosing to eliminate δ_a and ℓ_2 by combining Equations (1) through (4) yields weight as a function of ℓ_1 :

$$W = C_1 \ell_1^2 + C_2 \ell_1 + C_3 + \frac{C_4}{\ell_1} \tag{5}$$

where the constants are: (see next page)

$$C_1 = \frac{\rho_1 F_W F_\ell}{8 K \Delta T_1} (\sqcup - \sqcup')$$

$$C_2 = 2N\left\{2\rho_1 \delta_S \ell_S + 4\rho_P \delta_P \ell_S\right\} + 2\rho_c \delta_c \ell_c$$

$$C_3 = 2N\left\{2\rho_P A \delta_P F_P\right\} + 4\rho_c \delta_c \ell_c \ell_S$$

$$C_4 = 2NA\left\{2\rho_1\left[\ell_S \delta_S + \ell_F \delta_F\right] + 4\rho_P \delta_P\left[\ell_S + \ell_F\right]\right\} + 2A\rho_c \delta_c \ell_c$$

Since only weight variation is being considered, the term, C_3, that does not involve ℓ_1 may be omitted.

The derivative of Equation (5) can be set equal to zero and the resulting cubic equation solved to obtain the minimum weight configuration. However, more information is gained in a particular application by evaluating the constants in Equation (5) and plotting W vs. ℓ_1. A typical curve is shown in Figure 2. The optimum value of ℓ_1 is then selected from this graph and optimum values of ℓ_2 and δ_a are determined by substituting this value of ℓ_1 into Equations (2) and (3). The weight penalties for off-optimum dimensions are also shown by the curve.

This procedure determines cell dimensions for minimum system weight consistent with physical restraints and performance requirements. Weight penalties are also obtained from the resulting W, ℓ_1 curve for use when analyzing a system from standpoints other than minimum weight.

3.3 Fuel Cell Module Cooling Systems

After the heat produced in the fuel cell has been conducted to the outside of the cell, some means must be provided to remove the heat from the cell and reject it from the space vehicle. Since most space vehicles have some method of heat rejection, such as a radiator, evaporative cooler or sublimer, the investigations and discussion assume that a primary coolant loop served by such a heat sink is available. The possible fuel cell cooling systems may then be divided into two general categories:

1. Primary Cooling Systems
2. Secondary Cooling Systems

3.3.1 Primary Cooling Systems

Primary cooling systems are defined as those which use the space vehicles central cooling fluid to remove the waste heat directly from the fuel cell assembly. In such a case, the vehicle's primary coolant would come in direct contact with the fuel cell assembly. Design of such a system requires specific knowledge of coolant flow, coolant temperature limitations, and type of coolant. For example, if the available coolant is very cold and the flow rate is relatively low, distribution of flow to achieve a uniform temperature throughout the fuel cell assembly becomes a very difficult problem. The type of coolant must also be suitable for use in the fuel cell system. Since the secondary cooling system concept is more flexible than the primary cooling system, the systems which have been studied are secondary systems. Much of the knowledge gained from these studies could be applied in the special cases where the use of the primary cooling fluid is feasible.

3.3.2 Secondary Cooling Systems

Secondary cooling systems are those which use an intermediate fluid to transfer the heat from the fuel cell assembly to the primary coolant. This fluid, which could be either a gas or a liquid, would be circulated around the fuel cell assembly by a suitable pump or fan and then would pass through a heat exchanger where the heat would be transferred to the primary coolant. This basic cooling system is shown schematically in Figure 3.

3.3.2.1 Gas Cooling

Studies have indicated that a gas, such as hydrogen, is a feasible cooling fluid which offers a number of advantages. Under a corporate program a 35-cell module has been operated successfully using forced air cooling, thus confirming the feasibility of gas cooling. The gas cooling system has the advantage of being relatively simple, and suitable for use in zero gravity. In addition, a saving in system weight may be possible by using a gas coolant.

Development of such a cooling system requires development or procurement of four components.

1. Circulating fan and motor
2. Heat exchanger
3. Coolant temperature control
4. Ducting

Although these items must all be sized and designed for each specific system or configuration, considerable design information of a general nature may be obtained. For example, there are various types of fans and motors which must be evaluated with the special requirements of this system in mind. To name a few, there are vane axial, centrifugal, and squirrel cage blowers driven by d.c. power or 400 cycle a.c. power.

Laboratory testing has been started to evaluate some of the possible component designs. Testing to date has been limited to general feasibility of several blower-ducting configurations. The first tests were run on a squirrel cage blower. The feasibility of mounting the motor inside the blower rotor was checked in one of these tests. For the blower and motor tested, it was found that a drop in output of as much as 30% could be expected although design could probably improve this figure.

The fuel cell assembly will be cooled on two sides only. Thus a means must be provided for directing the coolant flow evenly across the two sides of the assembly. This can be done in a number of ways. Two separate fans and motors, or one motor with two fans, or one motor and fan with a double discharge scroll may be used. Since the latter design appears to be the most simple and reliable, a test was run to check the feasibility of this approach. The test setup, shown in Figure 4, was used to run the test. The fan was tested with the single scroll which was furnished with the blower to furnish a reference for the double scroll tests. For the scroll design tested, the double scroll had about 15% less output than the single scroll. Since a more refined scroll design would probably improve this figure, it can be concluded that the dual discharge scroll is feasible with a small reduction in blower performance.

Studies and testing will be continued on the various components of a gas cooling system. Most of the initial work will continue to be feasibility tests of various means of circulating and distributing the coolant gas. Methods of controlling the coolant temperature will also be studied.

3.3.2.2 Liquid Coolant

The principle advantages of the liquid cooling system are reduced pumping power and a smaller system volume. This type of cooling system has been incorporated into the breadboard recirculated system and has operated satisfactorily. The secondary liquid cooling system uses the same basic system schematic shown in Figure 3. In this case a pump replaces the blower and a different heat exchanger design is used. As in the gas cooling system, distribution of flow remains a prime consideration.

In selecting a cooling liquid there are several properties which must be considered. The property which limits the choice of coolants the most is the dielectric strength. Since the liquid will be in contact with the fuel cell plates, which are assumed to be uninsulated in this case, it must be as non-conductive as possible and must not be susceptible to electrolysis. The coolant selected must also have a relatively low freezing point. The specific heat and thermal conductivity should be as high as possible and the viscosity should be low to minimize the pumping power required. The coolant must be compatible with the materials with which it will come in contact.

The coolant selected for the recirculating breadboard system was Coolanol '35'. Coolanol 35 is a formulated product with a silicate-ester base. It has a specific resistivity of 11.0×10^{10} at 100° C and a dielectric strength at 25° C of 470 volts/mil. The specific heat is 0.46 Cal/gm° C at 25° C which is approximately one-half that of water and slightly less than glycol. Reference literature indicated that Coolanol should be compatible with all the materials which it contacted in the breadboard system. In order to determine what effect an oxygen leak into the coolant loop would have, a sample of Coolanol was maintained at a temperature of about 90° C for an extended period of time with oxygen bubbling through it. There was no detectable effect on the Coolanol.

Aside from searching for better cooling liquids, the areas which require additional investigation are flow distribution and temperature control. For flight hardware, of course, additional work would be necessary to optimize weight and volume of all system components.

4.0 BREADBOARD SYSTEM OPERATION

During the period covered by this report, the breadboard system was revised as discussed in the previous quarterly report. Three major changes to the system were made. (1) All components were mounted directly on the fuel cell module end plate. This eliminated the bypass valves and the extra mounting plate. (2) An oxygen purge system consisting of a timer and solenoid valve was substituted for the oxygen recirculation system. This change reduced the parasitic load by about 25%. The system weight and volume were reduced by a similar amount through elimination of the oxygen recirculation pump and the oxygen condenser-separator, and the associated controls. (3) The liquid cooling system was extended to include cooling the fuel cell module in addition to controlling the condenser temperature. The schematic diagrams of the revised reactant supply system and cooling system are shown in Figures 5 and 6, respectively.

The breadboard system operated satisfactorily under a 30 amp load for a total of 152 hours with Coolanol as the system coolant. After initial setting of the various controls, no adjustment was necessary during the operating period which included several start-up and shut-down cycles. This is a significant accomplishment since it shows that the control system is stable even with a relatively unrefined system using commercially available or developmental components. The proven ability to operate with hydrogen recirculation only, and just an occasional oxygen purge, is also a very definite improvement from the standpoint of system weight and simplicity.

During initial testing, an intermittent purge was used which averaged 3% of the amount of oxygen consumed. Further experimentation showed that a purge averaging 4.3% produced better performance, therefore this rate was used during the remainder of the test period. Since the plate design used in this module is not one of the more recent, improved designs, a reduction in the purge requirement could be expected with use of a new plate design.

The water removed from the system was collected, analyzed and found to be potable.

The Viton shaft seals for the hydrogen pump, which were mentioned in previous reports, operated with no detected leakage.

After completion of this series of tests, the breadboard system was revised to make use of the improved condenser-separator and remote sensing mixing valve which were discussed in previous reports. The condenser-separator is fabricated from nickel plated magnesium instead of from plexiglas. One plate has cooling fins to improve the heat transfer from the condenser. Initial tests indicated that, in addition to smaller size and lighter weight, the new condenser-separator should provide improved water removal characteristics. The remote sensing mixing valve receives a temperature signal from the gas leaving the condenser. The signal actuates the valve to control the proportion of hot and cold coolant admitted to the condenser. Since the gas temperature is the temperature which must ultimately be controlled, the new valve should provide better system response and more accurate control. Monthly Report Number 11 contains a detailed description of the mixing valve and Monthly Report Number 15 contains a detailed description of the condenser-separator.

After an initial system checkout, the seven-cell module, which had been used in all previous testing, was disassembled, inspected and rebuilt to assure a proper test of the revised system. Upon inspection, the old style, flat rubber gasket seals were found to be considerably deformed. In some cases the seal had extruded over the gas manifolding holes to the extent that reactant flow may have been partially obstructed. The result would probably be an extremely uneven flow distribution between cells of the module. Special inserts were machined to eliminate the extrusion of the seals when the module was reassembled. Utilization of recent improvements in plate fabrication techniques and 'O' ring seals would eliminate this problem. Because work on this system may be concluded, and extensive reworking of the plates would be required, the improved plate and seal techniques were not incorporated into this design.

Initial testing of the reassembled system indicated that the new components were functioning well. The metal condenser-separator appeared to respond very well to changes in load as evidenced by the corresponding change in water removal rate. Figure 7 illustrates this response to changes in load between 15 amps and 30 amps. The condenser-separator also functioned well with the fuel cell operating at rated output, of 40 amps. As Figure 8 illustrates, the water removal rate was very close to the theoretical 40 amp water removal rate. The slight difference may be accounted for by the water removed with the purge gases.

The first test of the remote sensing mixing valve showed that the gas temperature leaving the condenser-separator was held within 1° C when the coolant supply temperature varied approximately 40° C. Although further testing will be necessary to completely evaluate the valve, the response and control appeared to be excellent.

Performance of the module was good although some difficulty was experienced with the bottom cell. It appeared that the erratic performance of this cell was linked to the operation of the cell cooling system. Since this is the end cell, flow distribution or temperature variations would have a much greater effect than on the remaining cells. Under typical operation, the total voltage was about 5.75 volts at rated load of 40 amps, which is an average cell voltage of .82 volts. The system was still under test at the end of this reporting period.

5.0 FUEL CELL PLATE FABRICATION

In the past, the magnesium fuel cell plates have been machined from plate stock. Various methods are being investigated to determine if there are better or more economical ways of fabricating the plates in various quantities.

1. Conventional Milling

   This method has proved to be the most satisfactory method in the past. The quality of the plates is very good and plating for corrosion protection has been no problem since the plates have smooth, pore free surfaces. Cost can be reduced for medium quantities by use of the taped machining process. Improvement in quality and reduction in cost may be possible by using one or more of the special processes below for operations which are difficult or time consuming for the milling machine.

2. Chemical Machining

   A study of machining fuel cell plates by various chemical methods has been made by Williston Engraving Company, Milwaukee, together with Dow Chemical Company Laboratories. These studies indicated that chemical machining is not an economical method of machining the entire fuel cell plate. It may, however, be advantageous to machine certain surfaces by this method, thus reducing the cost of conventional machining.

3. Die Casting

   Dow Chemical Company Laboratories have investigated the possibility of forming fuel cell plates by the die casting method. Consideration was given to the nickel plating problems associated with die cast material as outlined in a letter to us from Furniture City Plating Company. Dow Chemical Company has expressed their confidence in developing a magnesium alloy which will produce satisfactory die cast fuel cell plates.

   Due to the high cost of dies, this method of forming plates does not become economical until a minimum of about 100 identical plates are required. This appears to be a promising method and investigations will be continued.

4. Stamping

   It appears that stamping may be feasible for some simple plate designs. Tool cost is less than for die casting and thus stamping may be more economical for medium quantities. One disadvantage of this method is the low ductility of magnesium. Hot working would probably overcome this disadvantage and make it feasible for some plate designs.

5. Electrical Discharge Method (EDM)

A sample plate has been machined by EDM. For some plate designs it appears feasible and economical for small quantities, however, poor surface finish makes it relatively unattractive in most cases.

6. Electro-Chemical Machining

This method appears to have some merit and is being investigated.

The methods considered were evaluated for fabrication of magnesium only, since this has the best combination of thermal properties and density for the present cell designs. It should also be noted that in the future, any of the methods considered may be feasible for special plate configurations and thus must be reconsidered as the plate designs change.

6.0 CONCLUSIONS

It can be concluded from the analysis in Sections 3.1 and 3.2 that the weight of a fuel cell assembly for any specific application will depend upon the allowable temperature differences in the cell plate and can be optimized by selection of the plate length-to-width ratio. The secondary cooling system, due to its flexibility in application, is the most promising type of system. Use of either a gas or a liquid cooling fluid is feasible and each has its advantages which must be further investigated. The Dynamic Vapor Pressure Control breadboard system has been proven to operate satisfactorily with only hydrogen recirculation. Of the magnesium fuel cell plate fabrication methods investigated to date, die casting appears to be the most economical method for large quantities of plates provided a suitable alloy can be developed. Conventional milling as used in the past still appears to be the best way of producing high quality plates without a considerable investment in development.

7.0 FUTURE WORK

During the time this contract has been in effect, a new system of controlling the moisture content of fuel cells has been developed. This system, called Static Vapor Pressure Control, is inherently simpler, more reliable and more compact than the Dynamic Vapor Pressure Control system as indicated by the feasibility studies carried out under Contract No. NAS8-5392. Although the latter system operates well and the development is proceeding very well, it was felt that the new system has a greater potential as a simple and reliable system for use in space vehicles. As a result, it was recommended that the contract be revised to substitute development of the Static Vapor Pressure Control System. In anticipation of this revision, plans are being made to bring the dynamic system breadboard model tests to a logical conclusion. In addition, plans are being made to start work in the following areas during the next quarter.

1. Continue thermal design tests and studies as applied to the Static Vapor Pressure Control System.

2. Study the operation of parallel connected sub-modules.

3. Test various cell constructions for the purpose of improving life, reliability and performance.

4. Study the mechanisms of Static Vapor Pressure Control including tests using the gas chromatograph.

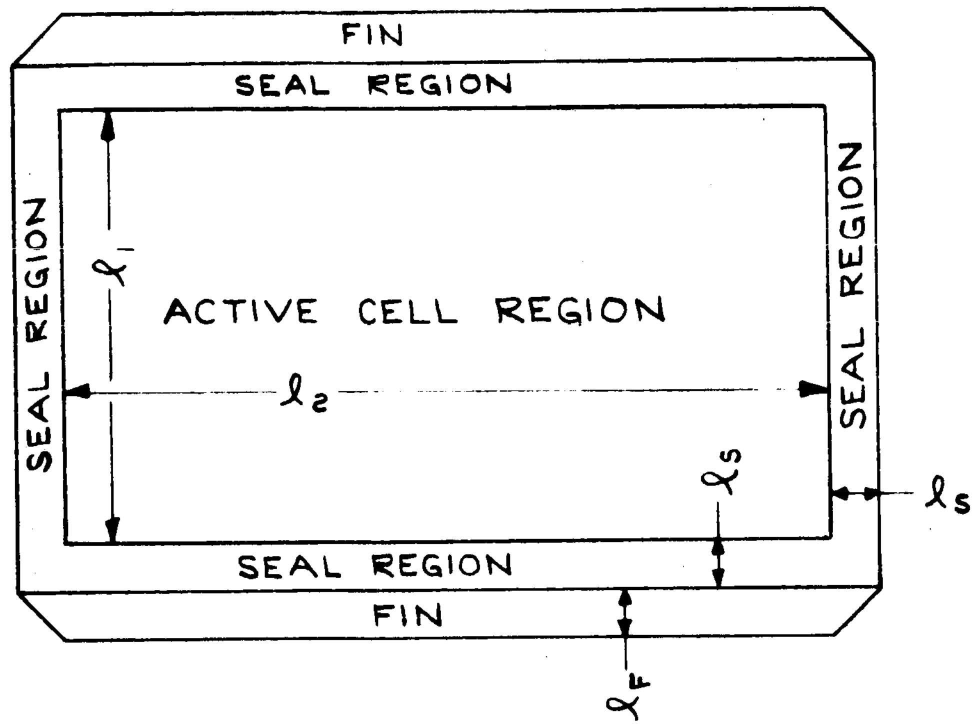


FIGURE - 1

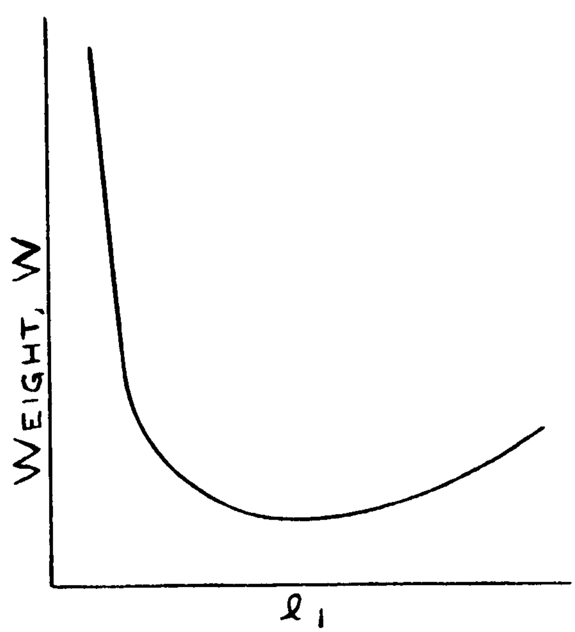
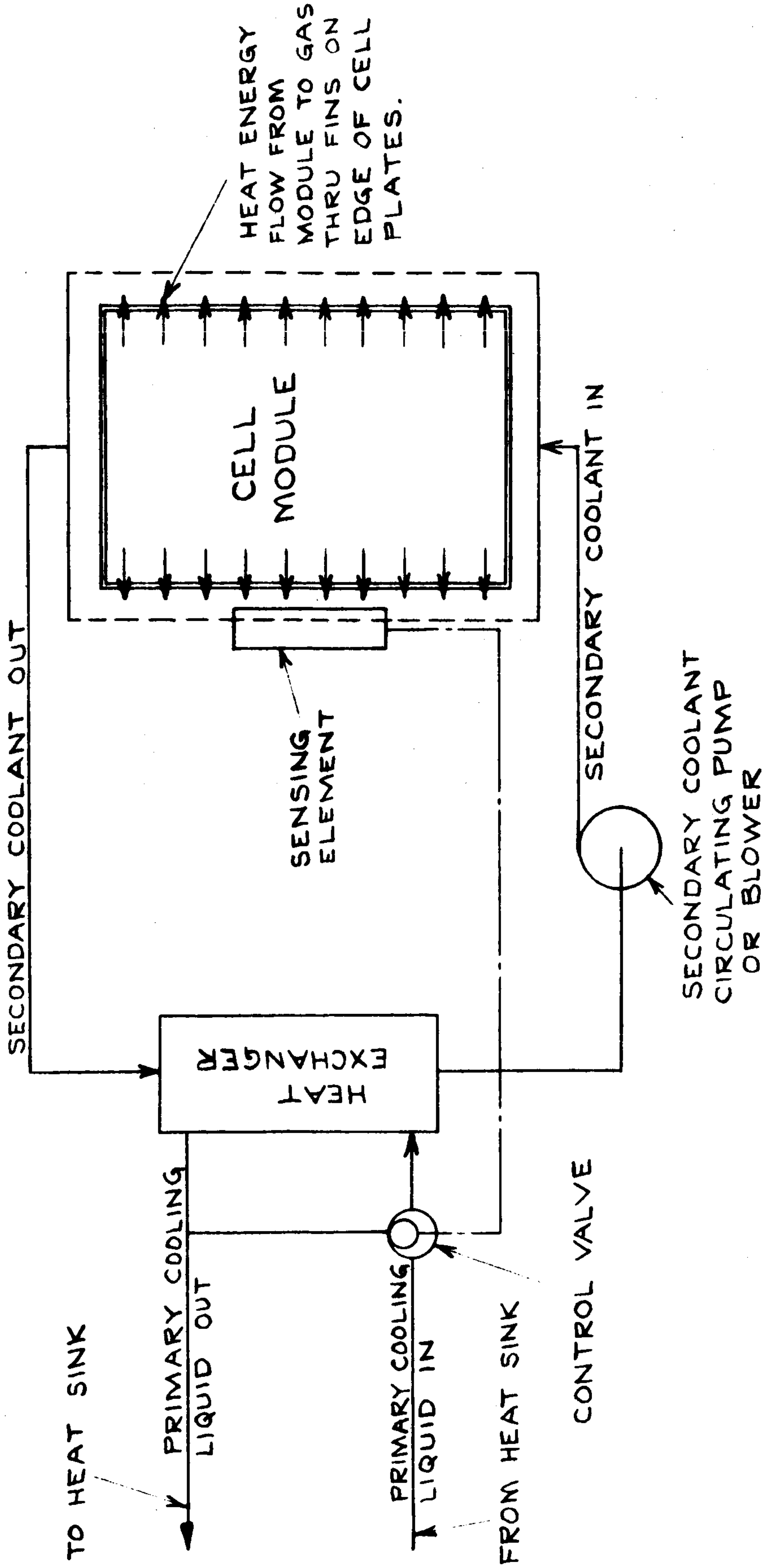


FIGURE - 2



SCHEMATIC COOLING SYSTEM - FUEL CELL MODULE

ALLIS - CHALMERS MFG. CO.

FIG. - 3

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1-SK-63287-2

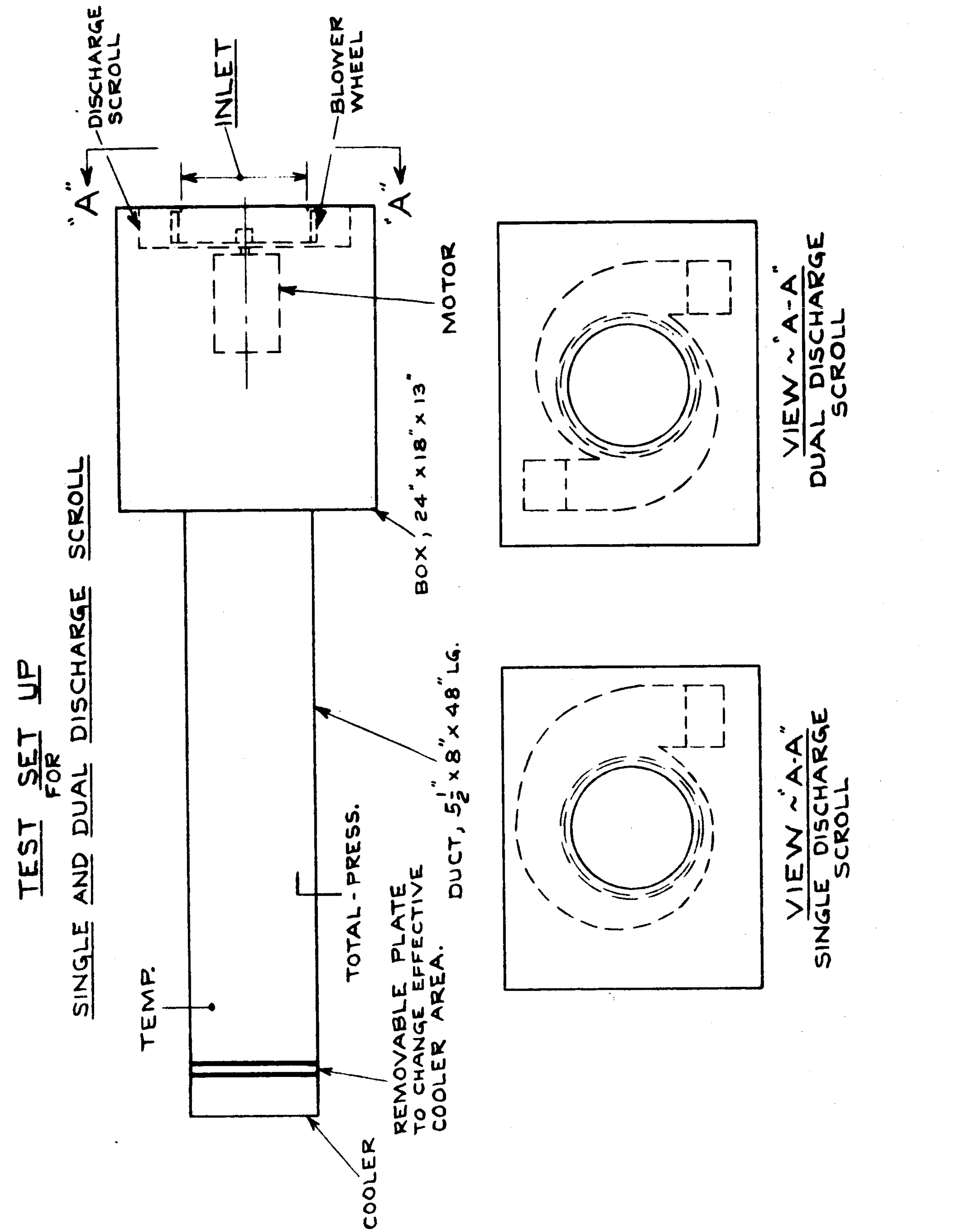

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FIG.-4

H.P.B. 10-8-63
1-SK-63287-5

SCHEMATIC OF FUEL CELL GAS SYSTEM (REV. A)

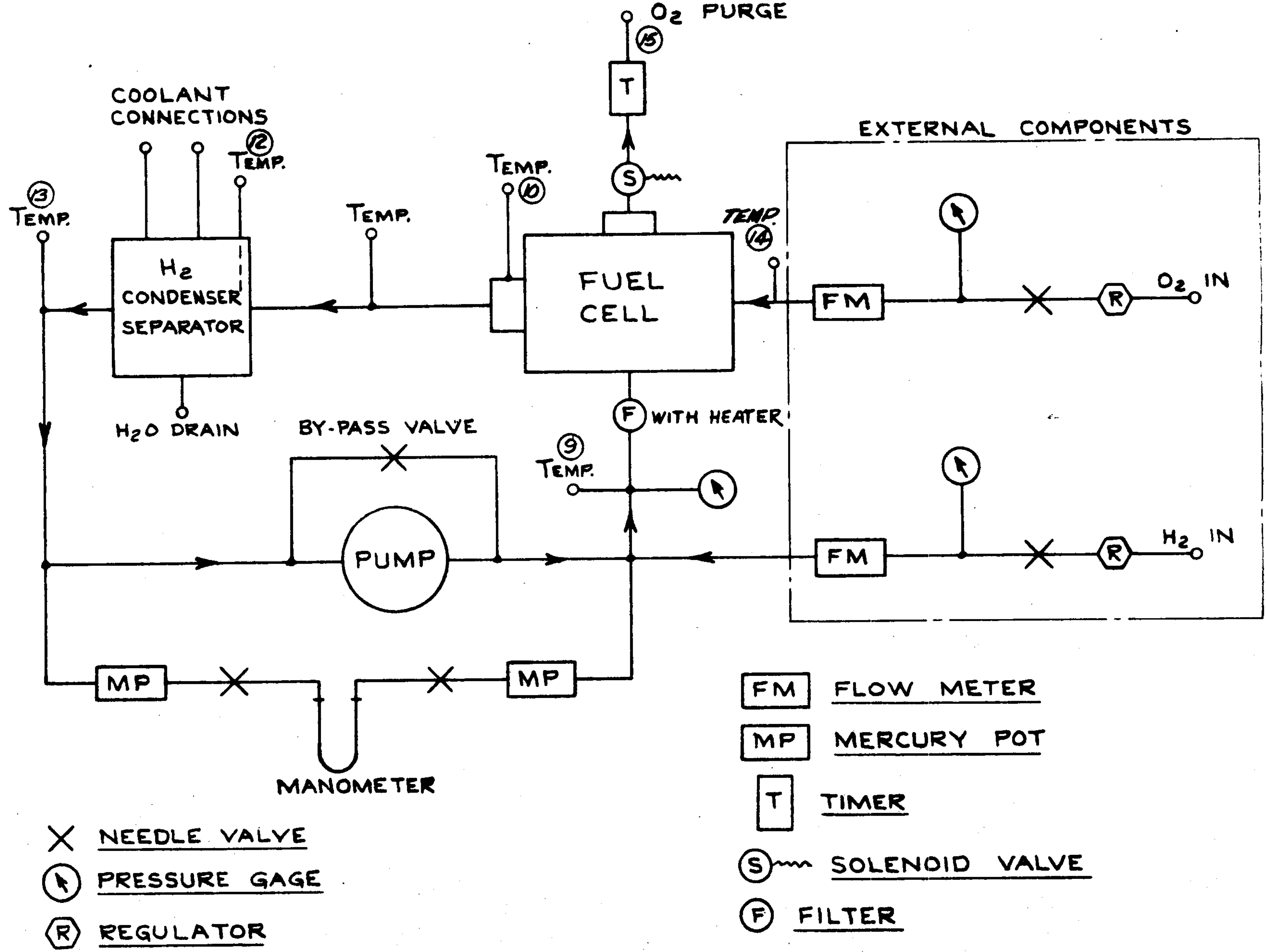
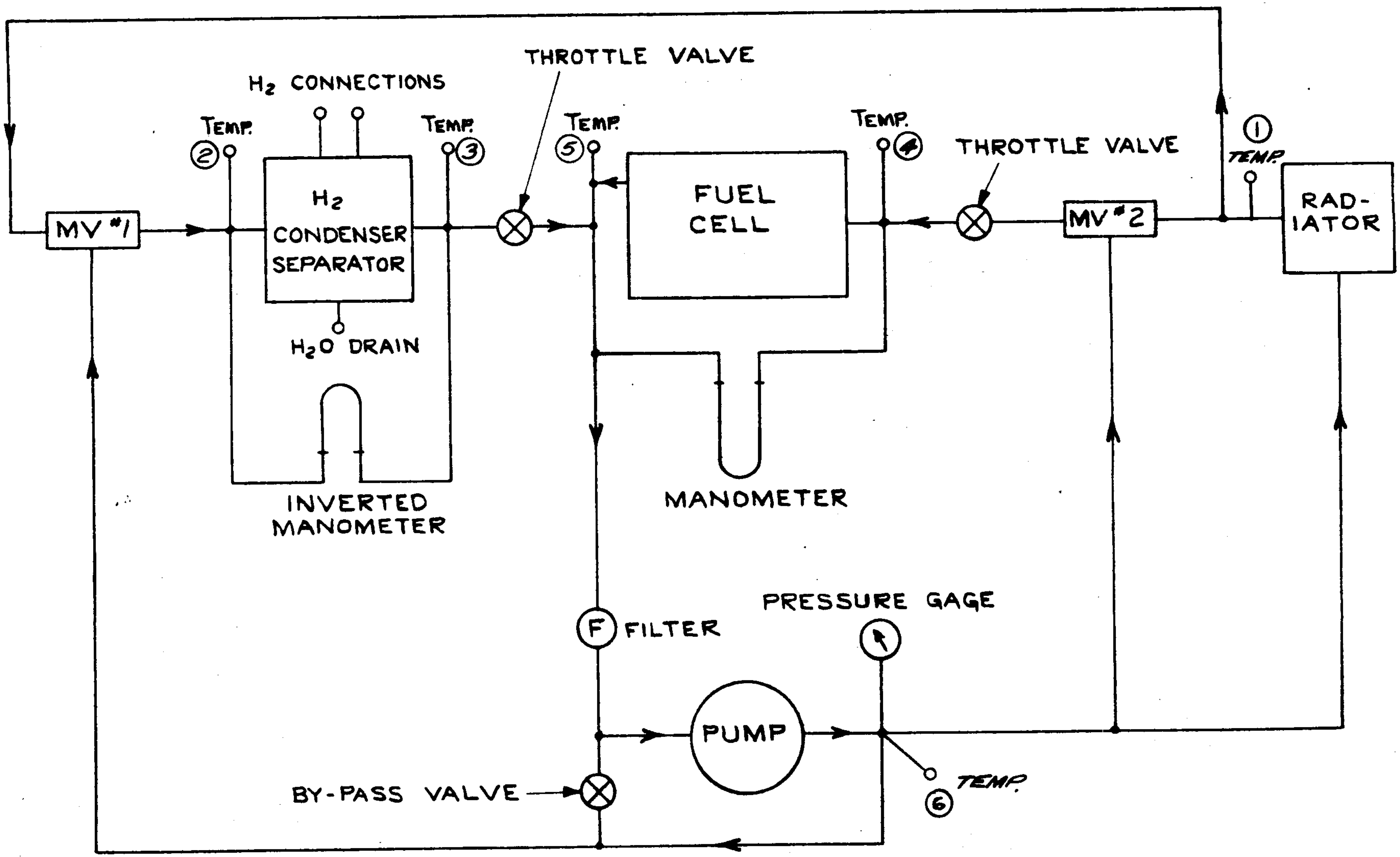


FIG. No. 5

ALLIS-CHALMERS MFG. CO.

REV. #1 H.P.B. 7-26-63
H.P.B. 6-11-63
1-SK-63175-51 A



MV MIXING VALVE

SCHEMATIC OF FUEL CELL COOLING SYSTEM (REV. A)

ALLIS-CHALMERS MFG. CO.

FIG. No. 6

REV. #2 H.P.B. 7-26-63
REV. #1 - H.P.B. 7-23-63
H.P.B. 6-7-63

1-SK-C3175-50A

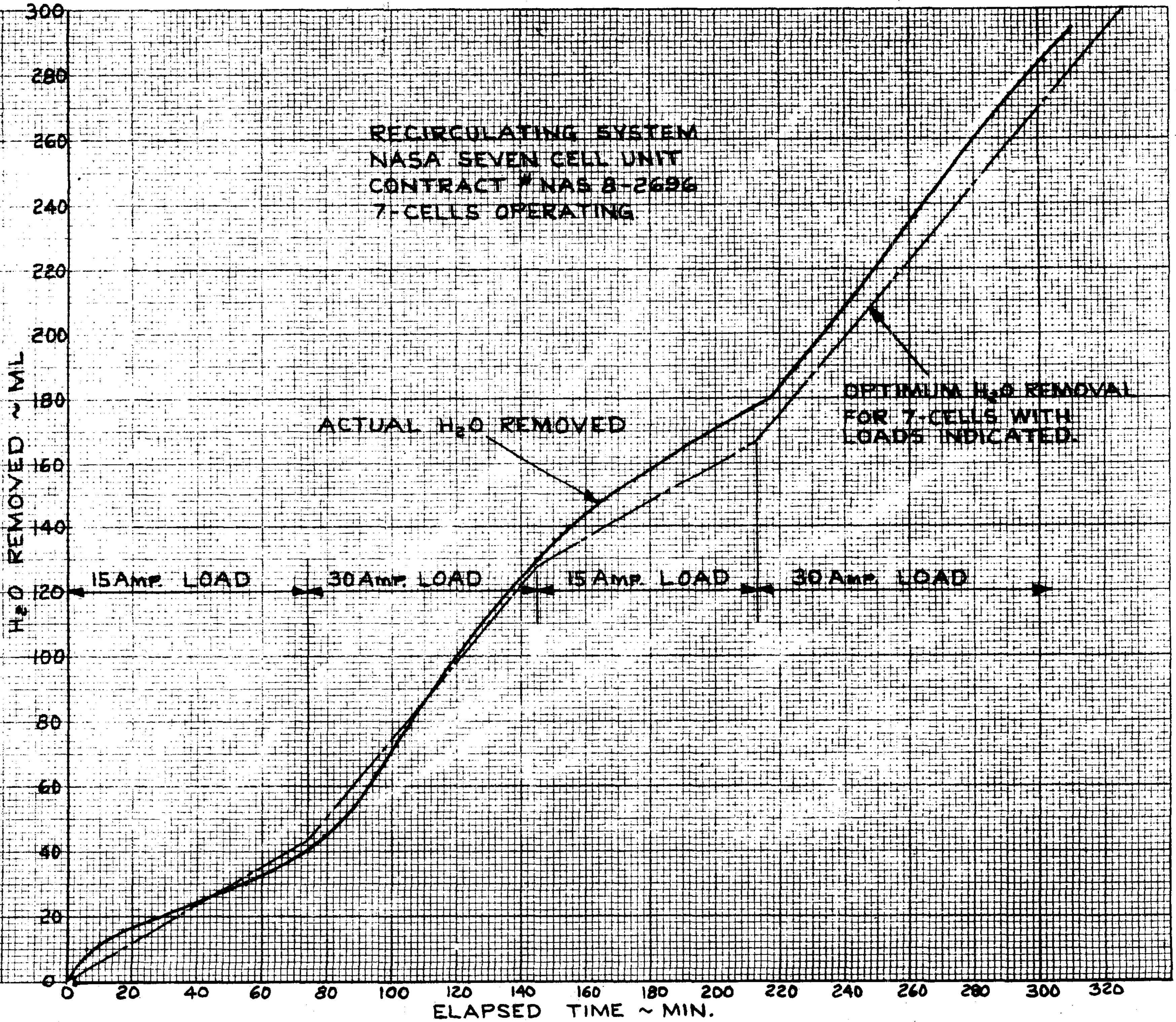


FIG. No. 7

ALLIS-CHALMERS MFG. CO.

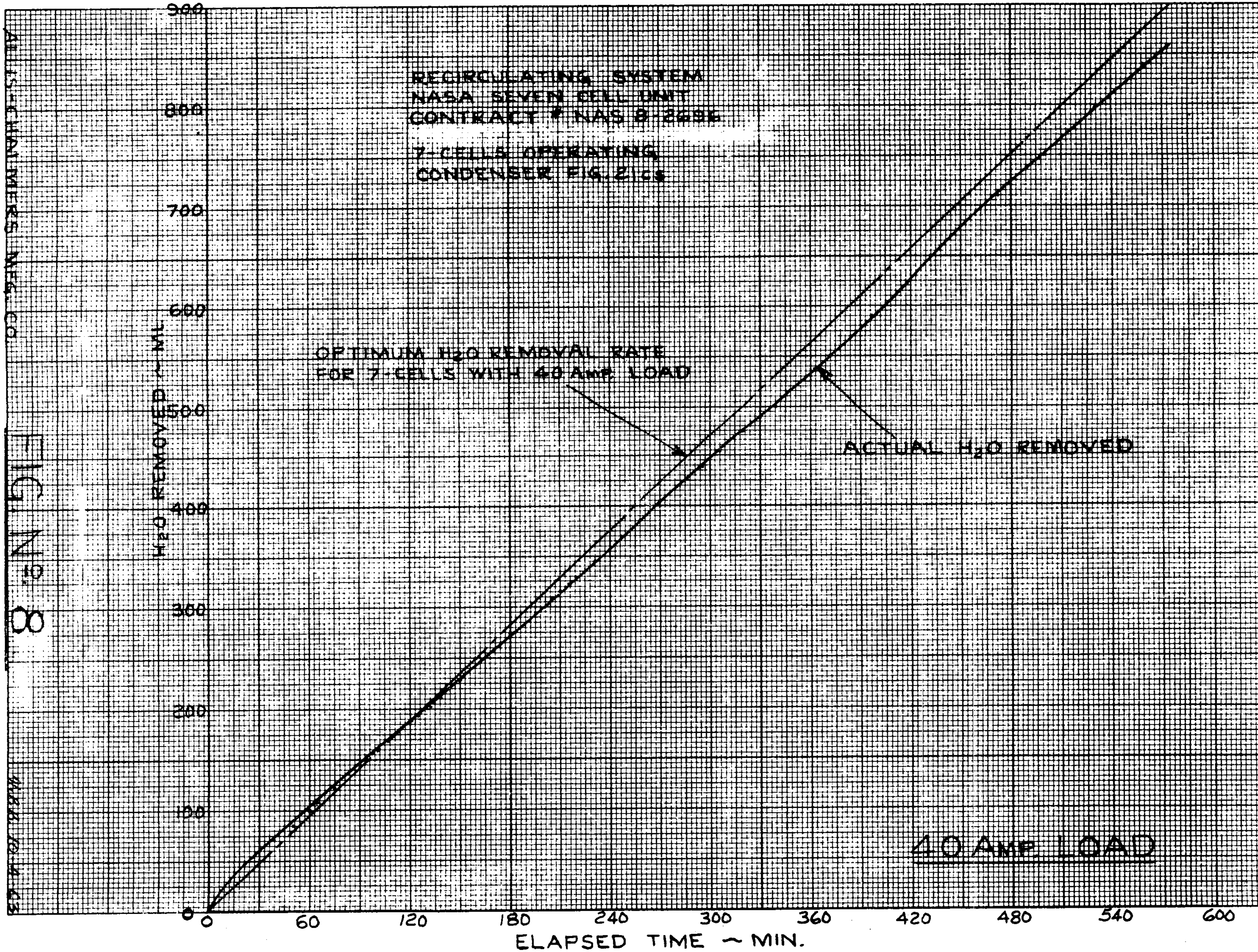


FIG. No. 8

1-SK-63280-5A